METAMORPHIC HISTORY OF A LARGE OPAQUE NODULE IN CRYSTALLINE EUCRITE ASUKA 881388.
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ABSTRACT. The fine-grained, crystalline eucrite Asuka (A-) 881388 includes an unusually large sub-rounded opaque nodule with a tail appears distinct from the silicate phases, which are mainly polygonal pyroxene and plagioclase. The opaque nodule consists of ilmenite, titanian chromite, troilite, and Fe metal. The presence of this isolated large opaque nodule and fine-grained hypidiomorphic silicates suggests that A881388 may have an extremely high-temperature metamorphism, where pyroxene and plagioclase recrystallized, probably in a solid state, while opaque phases with lower melting points than the silicates (=later crystallization products) were selectively melted and migrated to form the seemingly independent opaque nodule.

INTRODUCTION. While most of eucrites are monomict or polymict breccias, A881388 is an unbrecciated crystalline eucrite. Despite its crystallinity, A881388 shows mineralogical features that record an extensive metamorphism. Here, we unravel its thermal history, focusing on a large opaque assemblage.

RESULTS. Preliminary mineralogical studies haves been done by one of us [1] and Yanai [2]. A881388 is a fine-grained crystalline rock and shows hypidiomorphic texture like Caldera [3]. Polygonal pyroxenes are 0.03 - 0.35 mm in diameter, showing fine (up to 1 μm) exsolution of augite, and plagioclases which are dominantly 0.05 - 0.18 mm in diameter. Pyroxenes and plagioclases are clear and free from "clouding" due to unmixed minute opaques, which are common in ordinary eucrites [4]. Small opaque phases such as ilmenite, troilite, and less abundant chromite, are scattered both in the grain boundaries of silicates, and within silicates, mostly in pyroxenes. An opaque assemblage that is unusually large (540 × 610 μm), compared with the silicate phases, is found at one corner of the polished thin section (PTS). This opaque nodule has a sub-rounded triangle shape with a short tail and seems to be distinct from the silicate groundmass. On one side of the PTS, a thin brown vesicular fusion crust (150 μm in average) is observed. This fusion crust is relatively heterogeneous, incorporating partly melted pyroxenes, rounded silica minerals, and opaque crystals (ilmenite and chromite).

The modal abundances of minerals in the opaque nodule are ilmenite 53 vol.%, chromite 34 vol.%, troilite 12 vol.%, and Fe metal 1 vol.%. Compositional data are shown in Table 1. Titanian chromites are slightly zoned and a reverse zoning is found from Ti-rich, Cr-poor cores ($Chr_{55}Ulv_{32}Her_{13}$) to Ti-poor, Cr-rich rim ($Chr_{62}Ulv_{25}Her_{14}$). Also note that Cr content in ilmenite decreases toward the boundary with titanian chromite. Some of ilmenite grains are seemingly oriented platy ones and others are massive. Fe metal (50 μm in size) is almost Ni-free and includes 0.32 wt% of Ti. Troilite crystallized along the rims of the nodule and includes 0.11 wt% of Ti. The outline of this nodule is subrounded with a chromite tail and seemingly forms a separated system from surrounding silicates. According to the rounded appearance of this nodule, it could have crystallized from a melt.

In addition to the large opaque nodule, smaller opaque grains (20 - 80 μm in size) are scattered throughout the PTS; some are found as isolated grains, and others are inclusions in pyroxenes (opaque inclusions in plagioclase are rarely recognized). Most of minute opaque phases are ilmenite and troilite. Less abundant chromites are found mainly as an intergrowth with ilmenite; probably these two phases cocrystallized. In one opaque, 75μm × 40μm in size, troilite, ilmenite and chromite coexist as in the opaque nodule. Ilmenite (50 μm in diameter) with a rim of chromite is also found in the fusion crust.

DISCUSSION. Reverse zonings of spinel have been reported for lunar samples. Two distinct processes were suggested for the reverse zoning: (1) subsolidus reduction and (2) subsolidus equilibration. A reverse compositional change of spinels, followed by subsolidus reduction of chromian ulvöspinel to ilmenite, Fe metal, and sometimes aluminian-titanian chromite has been reported for Apollo14 and 16 samples [5-9]. El Goresy and Ramdohr [10] reported chromian ulvöspinel mantled by ilmenite or coexisting with ilmenite in Ti-rich Apollo17 mare basalts shows a reverse zoning. These authors noted that the Apollo 17 ilmenites are not oriented along (111) planes of chromian ulvöspinel, as expected if they formed by subsolidus reduction of chromian ulvöspinel. El Goresy and Ramdohr [10] proposed that the ilmenite rims instead formed by a reaction between chromite and a melt, or by coprecipitation from the liquid around spinel. They suggested that the reverse zoning should have been formed due to a subsolidus equilibration involving ilmenite and chromian ulvöspinel, not due to subsolidus reduction.

In the opaque nodule of A881388, ilmenite did not crystallize as a rim of chromite: some ilmenites appear to be oriented and others are massive. The oriented platy ilmenite suggests decomposition of chromian ulvöspinel. A reverse zoning of chromite may be found by growth of ilmenite in higher-Ti-Cr complex compound. In another possibility, enrichment of spinel in chromite and a depletion in Cr_2O_3 in coexisting ilmenite toward the boundary with chromite may be produced primarily due to subsolidus equilibration by diffusion during an annealing episode. Subsolidus equilibration could completely erase a primary crystallization zoning trend of spinel (a zoning from Ti-poor, Cr-rich core to Ti-rich, Cr-poor rim).

Since Fe metals formed by reduction of FeS or FeO tend to include lower contents of siderophile elements [11], Fe metal with low Ni content (0.03 wt%) in the opaque nodule suggests its reduction origin. The Fe metal could be either by reduction of troilite, or a reduction of spinel into ilmenite and Fe metal. Therefore, both subsolidus reduction for the formation of producing Fe metal, and subsolidus equilibration for the reverse zoning of spinel might have occurred.

Equilibrium temperatures for coexisting ilmenite and titanian chromite in the presence of Fe metal was studied by

Knecht et al. [12, 13]. Coexisting chromite (Cr/(Cr+Ti) = 0.77-0.85) and ilmenite (Cr/(Cr+Ti) = 0.02-0.05) in the nodule are probably equilibrated slightly below 1000 ^{o}C.

According to Harlow and Klimentidis [4], clouding in eucritic pyroxenes formed unmixing of ilmenite, chromite, Fe metal, as a result of reduction of Cr-, Ti-rich pyroxene during subsolidus annealing. The clouding requires a condition of T ≈ 900^{o}C and fO_2 of 10^{-16} to 10^{-18} during slow cooling [4]. Since the solubility of TiO_2 and Cr_2O_3 in pyroxene depends on FeO concentration, the presence of clouding in pyroxene strongly depends on FeO content in pyroxene: Fe/(Fe(Mg) > 0.4 of pyroxene is necessary to precipitate opaques within pyroxene [4]. The average Fe/(Fe+Mg) = 0.6 in the A881388 pyroxenes is in favor of opaque precipitation in pyroxenes. Lack of clouding of pyroxene in A881388 could be due to removal of unmixed opaques during recrystallization. In ordinary eucrites, chromite occurs as a very minor interstitial phase and most of the Cr in the eucrites occurs as chromite clouding in pyroxene. Therefore, the unusually high abundance of titanian chromite in the opaque nodule might have been derived from chromite removed from pyroxene during recrystallization of A881388. Low-melting-point phases such as ilmenite and troilite found in the mesostases in eucrites (e.g. [14]) may be selectively partially melted during an annealing process and form an opaque nodule, incorporating a chromite component that is removed from pyroxene. The minimum temperature for selective melting of troilite plus Fe-metal (i.e., ignoring ilmenite, which requires further study) would be 988^{o}C, the eutectic point of the Fe-FeS system [15].

Ordinary eucrites often have a granoblastic pyroxenes areas, where clouded pyroxenes recrystallized into fine-grained clear polygonal crystals of low-Ca pigeonite and minor augite, together with chromite and ilmenite at grain boundaries [16]. High temperature shock events have been proposed to convert parts of cloudy pyroxenes into such the granoblastic areas [16]. The fine-grained polygonal grains of both pyroxene and plagioclase are consistent with the relatively extensive high temperature process of A881388.

Future experimental studies are required to constrain the formation process of this interesting opaque nodule.

In summary, we infer that the A881388 eucrite may have experienced the following events: (1) Formation of basaltic eucrite by primary crystallization from a magma. (2) Brecciation and shock deformation due to impact. (3) Reduction and annealing process about 900^{o}C to produce clouding in pyroxenes. (4) A subsequent high temperature recrystallization and prolonged annealing process for selective melting and subsolidus equilibration below 1000^{o}C.

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Table 1. Mineral compositions (wt%) in opaque nodule.

	ilmenite	chromite			Fe metal	troilite
SiO_2	0.00	0.02	0.05	Co	0.19	0.04
TiO_2	54.22	7.87	10.33	Fe	100.49	62.26
Al_2O_3	0.01	6.80	6.26	Ni	0.03	0.01
FeO	44.01	37.61	39.91	P	0.00	0.00
MnO	0.83	0.55	0.58	S	0.01	36.98
MgO	1.51	1.19	1.22	Si	0.00	0.00
CaO	0.02	0.00	0.05	Cr	0.35	0.13
Cr_2O_3	0.06	45.56	40.51	Ti	0.32	0.11
V_2O_3	0.00	0.57	0.53			
Total	100.66	100.17	99.44		101.39	99.53